SENSOR MATERIAL CHARACTERISATION FOR MAGNETOMETER APPLICATION

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A project report is submitted as partial fulfillment
of the requirements for the award of the
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APRIL 2004

"I declare that this project is the result of my own work except for the ideas and summaries of which I have clarified their sources."

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DEDICATION

Special dedication to my beloved husband Khairul Anuar and daughter Nurin Najihah , my parents, my parent-in-laws and my families for all your love, support and care.

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I would like to express my greatest appreciation to my project supervisor, Assoc. Prof. Dr. Zainal Alam Bin Haron for his excellent guidance, suggestions and contributions throughout this study. Also, I would like to convey my gratitude to all my friends who have been very supportive and cooperative in helping me out to complete this project successfully.

ABSTRACT

AC and DC magnetic field measurements require a highly sensitive and stable magnetic sensor. In order to achieve these requirements, good properties and criteria of magnetic materials are identified. A few types of different magnetic materials have been used to study their characteristics and effect towards magnetic fields. The ring cores made from several different types of magnetic materials are designed having the same dimension so that they can be compared among each magnetic material easily. For this project, single and dual rod cores have been used as a fluxgate sensor core to observe the resulting sensor performance. Both sensors are tested with two magnetic sources; permanent magnet bar and solenoids with different diameters of wires. The output of each fluxgate sensor was processed to identify their relation with the test magnetic field density.

ABSTRAK

Pengukuran dan gangguan medan magnet arus terus dan arus ulang-alik memerlukan penderia medan magnet yang mempunyai kepekaan yang tinggi dan stabil. Untuk menghasilkan penderia tersebut, ciri-ciri bahan magnet yang baik telah dikenalpasti. Beberapa jenis bahan magnet yang berbeza telah digunakan untuk mengkaji ciri-ciri dan kesannya terhadap medan magnet. Teras gelang yang diperbuat daripada bahan-bahan magnet tersebut direkabentuk dengan dimensi yang sama bagi membolehkan perbandingan dibuat dengan mudah. Selain itu, rod tunggal dan berkembar juga telah digunakan sebagai teras penderia fluxgate, untuk melihat prestasi setiap jenis penderia tersebut. Kedua-dua penderia tersebut telah diuji dengan menggunakan dua sumber bahan magnet iaitu bar magnet tetap dan solenoid dengan diameter dawai yang berbeza. Isyarat keluaran bagi setiap penderia fluxgate seterusnya diproses bagi mengenalpasti hubungannya dengan ketumpatan medan magnet.

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LIST OF SYMBOLS AND ABBREVIATION

H	-	magnetic field intensity
B	-	magnetic flux density
G	-	Gauss
T	-	Tesla
Hz	-	Hertz
DC	-	Direct current
AC	-	Alternating current
μ	-	permeability
μ_r	-	relative permeability
χ	-	susceptibility
μ_o	-	permeability in vacuum
μi	-	initial permeability
M	-	magnetization
H_c	-	coercive force
H_{ci}	-	intrinsic coercivity
M_R	-	remanent magnetization
B_R	-	remanent or residual flux density
B_s	-	saturation flux density
μ_d	-	differential permeability
E_p	-	primary voltage
E_o	-	secondary/output voltage
N	-	number of turns
N_p	-	number of primary winding
V_{sec}	-	Induced voltage

A	-	Cross section area
D	-	Demagnetization factor
f_r	-	resonance frequency
L	-	inductance
C	-	capacitor
l	-	length of coil
D_i	-	inner diameter
D_o	-	outer diameter
R_2	-	outer radius
R_1	-	inner radius
h	-	height of ring core
w	-	width of ring core
r	-	mean radius
I_{max}	-	maximum current

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CHAPTER I

INTRODUCTION

1.1 Foreword

In this chapter, the background, purpose, objectives, and the scope of the project are discussed.

1.2 Problem Statement

Magnetic field sensing technology has been driven by the need for improved sensitivity, smaller size, and compatibility with electronic systems. Nowadays, various types and applications of magnetic sensors are produced. The techniques used to produce magnetic sensors encompass many aspects of physics and electronics.

Magnetic properties of the core such as differential permeability, coercive force, and demagnetizing factor were contributed to the sensitivity of the sensor and in producing magnetometer with better performance. This project approached various types of materials with same geometry to compare which is most suitable to be used as the core sensor, in order to produce high sensitivity magnetic field sensor and to compete with existing sensor in the marketplace.

1.3 Objectives of The Project:

This project is motivated by the following objectives:

i. To be familiar with the state of the art in magnetometer design.

ii. To identify suitable magnetic field sensor configuration for DC magnetic measurements.

1.4 Scope of Project:

The scopes of the project are as followed:

i. To implement experimental works that related to magnetic measurements.
ii. To identify the core materials properties that is most suitable for producing high sensitivity magnetic field sensors.

CHAPTER II

LITERATURE REVIEW

Magnetic field sensors play an important and continuously increasing role in many fields of science and of modern technique. Early applications of magnetic sensors were for directions finding or navigation. But today, many more uses have evolved and the technology for sensing magnetic fields has also evolved driven by the need for sensitivity improvement, smaller size, and compatibility with electronic systems.

A number of papers have been published on fluxgate magnetometer, showing different types of configurations and explaining the mechanism, importance and use of each one. The first patent on the fluxgate sensor (in 1931) was credited to H.P. Thomas. Aschenbrenner and Goubau worked on fluxgate sensors from the late 1920s; by 1936 they reported 0.3nT resolution on a ring core sensor. Since the 1980s, magnetic variation stations with fluxgates supported by a proton magnetometer have been used for observing changes in the Earth's magnetic field. Fluxgate compasses are extensively used for aircraft and vehicle navigation. Forster [1] started to use the fluxgate principle for the nondestructive testing of ferromagnetic materials. The fluxgate principle is also used in current sensors and current comparators. Compact fluxgate magnetometers are used for navigation, detection and search operations, remote measurement of dc currents and reading magnetic labels and marks.

W. Hernandez [2] has been presented a fluxgate magnetometer for high magnetic fields (<100μT). He used ferrite as the material of the core and relatively high sensitivity and linearity characteristics have been achieved, which simplified the signal processing circuit. The fluxgate magnetometer used the ring core sensor geometry, which was found to be the best for low noise sensors [3]. This is well suited for elimination of offset and instabilities of the sensor with time and temperature variations.

Fluxgate sensors serve for the measurement of DC and low frequency AC magnetic field in the range of approximately 1nT to 1mT with possible resolution of 50pT. Their principle is based on modulation of the flux in the pick-up coil by changing the permeability of the ferromagnetic core by means of the AC excitation field [4]. According to [4], most of the fluxgate magnetometers work in the feedback mode to improve the sensor linearity and increase the measurement range.

Kurt Weyand and Volker Bosse [5] have developed a new fluxgate magnetometer for measuring both magnetic dc and ac fields, with frequencies up to 2 kHz. The magnetometer has been designed using a pulse-width modulator and has a resolution of 10nT. It is possible to link up ac field quantities with dc field standards in a simple way.

Fluxset sensor is a new type of magnetometer sensor, which belongs to the family of fluxgate sensors. It has been developed and capable of measuring DC and AC (up to 200 kHz frequency) low-level magnetic fields with high accuracy. This device has sensitivity better than 100pT, operates in a wide temperature range, simple and cheap. Fluxset sensor that realize by using thin permalloy films, was developed in 2 different version; the high sensitivity version operates at DC or in low frequency range (below 100Hz) and high frequency version operates at AC up to a frequency of 100kHz [6].

Magnetic properties of the core such as differential permeability, coercive force, and demagnetizing factor were contributed to the sensitivity of the sensor [7]. The most sensitive materials are ferromagnetic. It has a high relative permeability. Ferrite, a composite material with high permeability, high resistivity, high Curie temperature and low coercive force had been chosen as the core for the fluxgate sensor. This is because the high resistivity of ferrite will decrease the eddy current losses when it is driven with high frequency alternating current. According to P. Ripka [1], ring core geometry fluxgate sensors have lower signal-to-noise ratio compared with open-end geometry fluxgate sensors.

The ring core fluxgates have in general low sensitivity, but they exhibit low noise in the input field units [8]. Rod core (Vacquier or Forster type) fluxgate sensors are very sensitive to the measured fields and resistant against perpendicular fields, but they have constructional problems and disadvantages coming from the existence of the core ends.

CHAPTER III

THEORETICAL BACKGROUND

3.1 Introduction

The earliest magnetic field detectors allowed navigation over trackless oceans by sensing the Earth's magnetic poles. Magnetic field sensing has vastly expanded as industry has adapted a variety of magnetic sensors to detect the presence, strength, or direction of magnetic fields not only from the Earth, but also from permanent magnets, magnetized soft magnets, vehicle disturbances, brain wave activity, and fields generated from electrical currents. Magnetic sensors can measure these properties without physical contact and have become the eyes of many industrial and navigation control systems.

3.2 A Review of Magnetic Sensor

Magnetic sensors differ from most other detectors in that they do not directly measure the physical property of interest. Devices that monitor properties such as temperature, pressure, strain, or flow provides an output that directly reports the desired parameter, as shown in **Figure 3.1.**

Magnetic sensors, on the other hand, detect changes, or disturbances, in magnetic fields that have been created or modified, and from them derive information on properties such as direction, presence, rotation, angle, or electrical currents. The output signal of these sensors requires some signal processing for translation into the desired parameter. Although magnetic detectors are somewhat more difficult to use, they do provide accurate and reliable data, without physical contact.

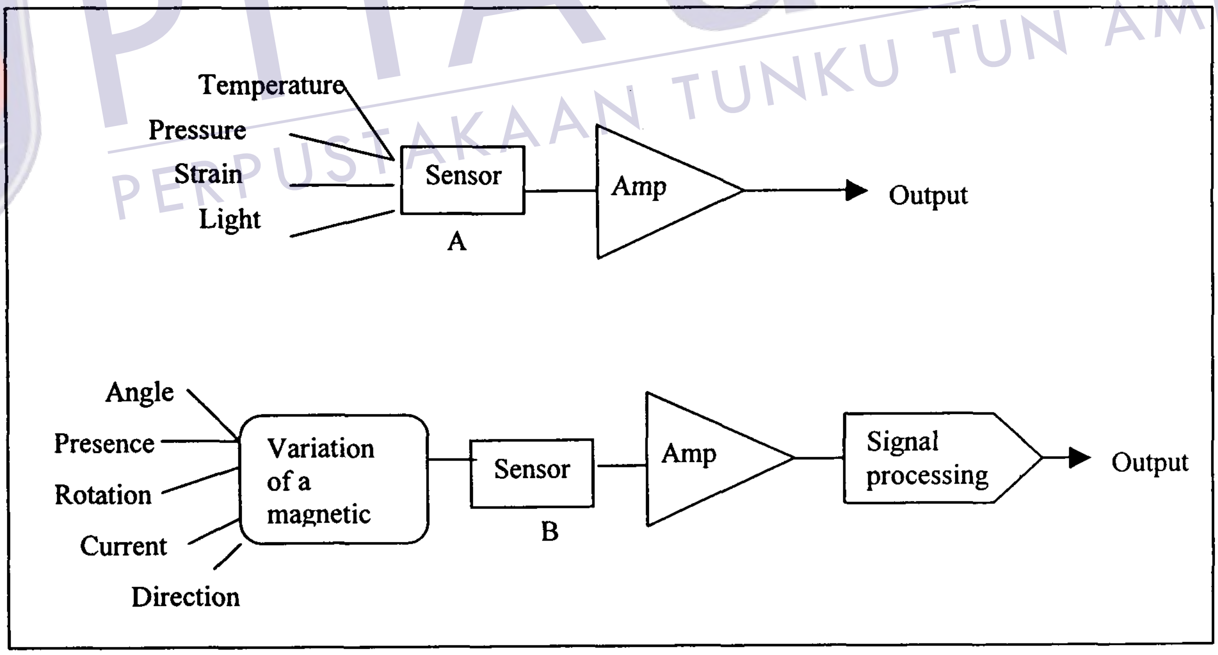


Figure 3.1: Conventional sensor versus magnetic sensing [3]

The magnetic field is a vector quantity that has both magnitude and direction. Magnet sensors measure this quantity in various ways. Some magnetometers measure total magnitude but not direction of the field (scalar sensors). Others measure the magnitude of the component of magnetization, which is along their sensitive axis (omni-directional sensors). This measurement may also include direction (bi-directional sensors). Vector magnetic sensors have 2 or 3 bi-directional sensors.

3.3 Magnetic Sensor Applications

There are a multitude of magnetic sensor applications, many of which are encountered everyday. However, the many applications can all be sorted into three basic categories. The distinction between each category is determined by how the sensor is used in relation to the ever-present Earth's magnetic field. **Table 3.1** defines the three categories and lists their major applications and most common sensors.

The boundary between categories 1 and 2 results from the magnitude of Earth's magnetic field, which varies from roughly 0.1G to 1G. For category 1, Earth's magnetic field acts as the limiting noise source. The boundary between categories 2 and 3 is the level to which Earth's magnetic field is stable.

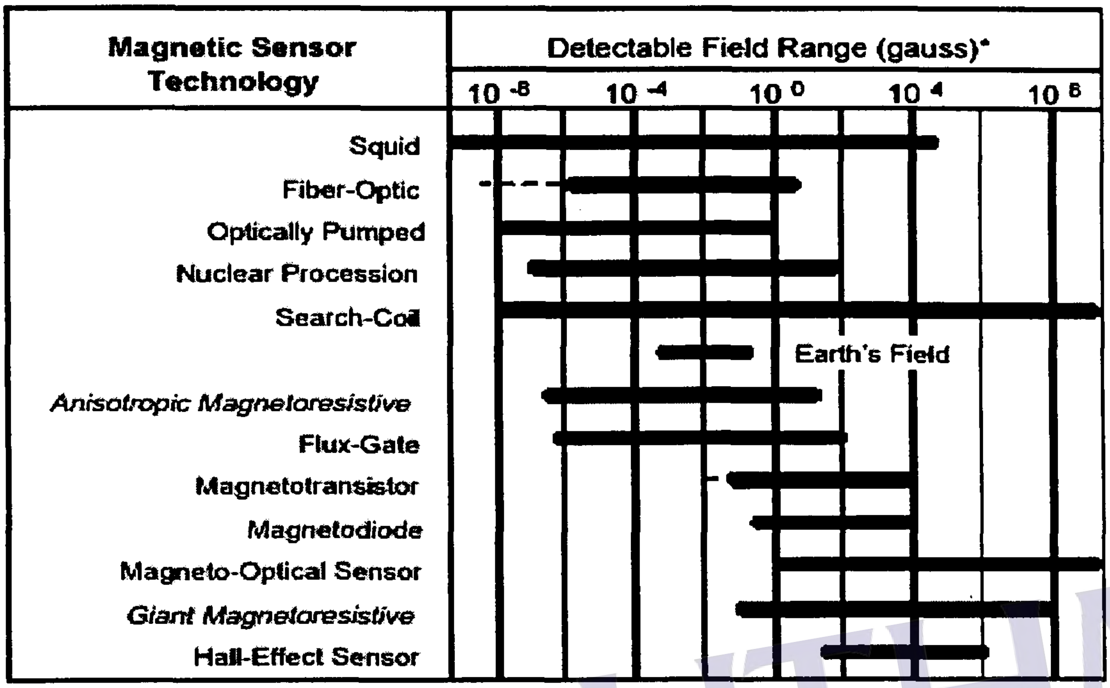
Table 3.1: Categorization of magnetic sensor applications [3]

	10^{-5} G	1 G
Category 3 High Sensitivity	Category 2 Medium Sensitivity	Category 1 Low Sensitivity
Definition - Measuring field gradients or differences due to induced (in Earth's field) or permanent dipole moments	Definition - Measuring perturbations in the magnitudes and/or direction of Earth's field due to induced or permanent dipoles	Definition - Measuring fields stronger than Earth's magnetic field
Major Applications - Brain function mapping - Magnetic anomaly detection	Major Applications - Magnetic compass - Munitions fuzing - Mineral prospecting	Major Applications - Non-contact switching - Current measurement - Magnetic memory readout
Most Common Sensors - SQUID gradiometer - Optical pumped magnetometer	Most Common Sensors - Search coil magnetometer - Fluxgate magnetometer - Magnetoresistive magnetometer	Most Common Sensors - Search coil magnetometer - Hall-effect sensor

3.4 The Present Technology of Magnetic Sensors

Magnetic sensors have been in use for well over 2,000 years. Early applications were for direction finding, or navigation. Now, magnetic sensors are still a primary means of navigation but many more uses have evolved. The technology for sensing magnetic fields has also evolved driven by the need for improved sensitivity, smaller size, and compatibility with electronic systems. **Table 3.2** lists the various sensors technologies and illustrates the magnetic field sensing ranges.

Table 3.2: Magnetic Sensor Technology Field Ranges
(source: *http://www.ssec.honeywell.com*)



* Note: 1gauss = 10^{-4} Tesla = 10^{5} gamma

Figure 3.2, 3.3, 3.4 and **3.5** shows the various types of magnetic field sensors in present technology.

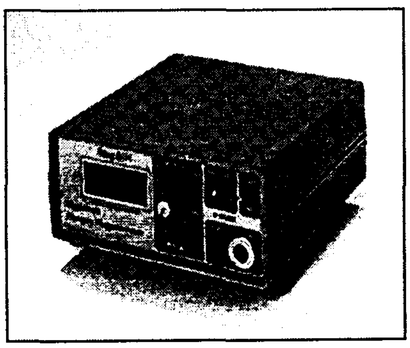


Figure 3.2: Bartington Fluxgate Magnetometer Mag-01(H)

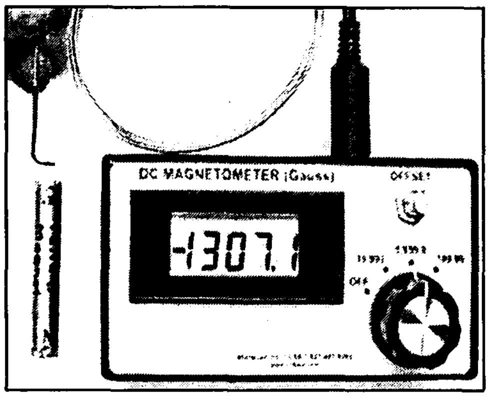


Figure 3.3: DC magnetometer (Gauss meter)

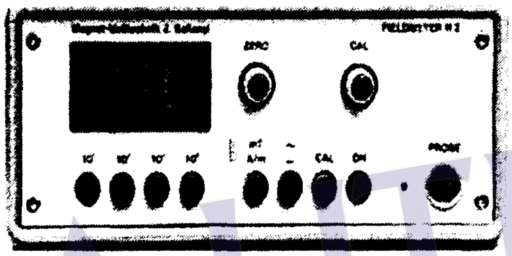


Figure 3.4: Portable Gaussmeter H2 for AC and DC operation

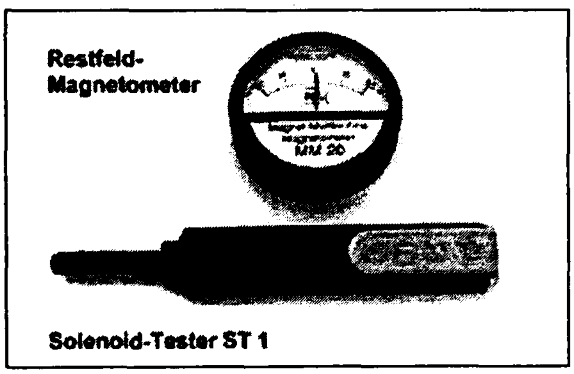


Figure 3.5: Restfeld (Analog) Magnetometer

3.5 Fluxgate Magnetometer

Fluxgate magnetometers, also known as saturable-core magnetometers, were first introduced in the 1930's for measurement of the Earth's magnetic field. Early development was for airborne magnetic surveys and for submarine detection during World War 11. They were further developed for geomagnetic studies (air-borne, seaborne, and underwater), for mineral prospecting, and later for magnetic measurements in outer space. They have also been adapted and developed for various detection and surveillance devices, both for civilian and military use. Despite the advent of newer technologies for magnetic field measurement, fluxgate magnetometers continue to be used successfully in all of these areas, because of their reliability, relative simplicity, economy, and ruggedness [4].

The instrument of fluxgate magnetometer consists of two identical ferromagnetic cores with properties such that the geomagnetic field can induce a magnetization that is substantial in the cores. Identical primary and secondary coils are wound in opposite directions around the cores and an alternating current (50-1000 Hz) is passed through the primary coils (thereby generating an alternating magnetic field). The alternating magnetic field induces an alternating voltage in the secondary coils.

Since the coils are wound in opposite directions, the voltage in the coils is equal and opposite in sign and their combined output is zero if there is no external field. In the presence of an external field, like the Earth's magnetic field, the magnitude of the combined voltage is proportional to the amplitude of the external field component. The fluxgate magnetometer is a continuously recording instrument and is relatively insensitive to magnetic field gradients over the length of the cores.

3.6 Magnetic Materials

Magnetic materials are used in applications such as power supply transformers, audio transformers, AC and RF Filter inductors, broadband and narrow band transformers, damping network, EMI/RFI suppressors, etc. The basic characteristic of magnetic materials is the permeability (μ). It is a measure of how superior a specific material is than air as a path for magnetic lines of force (Air has a μ of 1). Another characteristic of magnetic material is saturation. It is the maximum value of magnetic induction at specified field strength. When a material is saturates, it losses its linearity. Magnetic materials are available in many different types and sizes.

3.6.1. Classification of Magnetic Materials

The various different types of magnetic materials are traditionally classified according to their bulk susceptibility (χ). The first groups are materials for which χ is small and negative $\chi \approx -10^{-5}$. These materials are called *diamagnetic*; their magnetic response opposes the applied magnetic field. It has a very low value of relative permeability, μ_r. Examples of diamagnets are copper, silver, gold bismuth and beryllium.

A second group of materials for which χ is small and positive and typically $\chi \approx 10^{-3}$-10^{-5} are the *paramagnetic*. The permeability of paramagnetic materials is very close to that permeability what is in the vacuum. Their magnetic properties are almost neutral. The magnetization of paramagnetic is weak but aligned parallel with the direction of the magnetic field. Examples of these materials are aluminum, platinum and manganese.

The most widely recognized magnetic materials are the *ferromagnetic* solids for which the susceptibility is positive, much greater than 1, and typically can have values $\chi \approx 50$ to 10 000. These materials are easy to magnetize since they have a high value of relative permeability. Examples of these materials are iron, cobalt and nickel and several rare earth metals and their alloys [2].

3.6.2 Magnetic Properties of Ferromagnetic

Generally, ferromagnetic materials have very large values of relative permeability and susceptibility. These are important quantities and contribute to the sensitivity of the magnetic sensor.

One of the high quality materials in ferromagnetic group is ferrite. Ferrites are ceramics materials that can be magnetized to a high degree. The basic component is iron oxide combined with binder compounds such as nickel, manganese, zinc or magnesium. Two major categories of ferrites are manganese zinc (MnZn), and nickel zinc (NiZn).

Ferrites can be manufactured to very high permeability (over 15,000) with little eddy current losses. However, the high permeability of the ferrite makes it unstable at high temperatures, and saturates easily (even could be damaged by high saturation). Ferrites are suitable for applications such as DC-to-DC converters, magnetic amplifiers, EMI/RFI suppressors, transformers and inductors. Ferrite cores can be gapped to avoid saturation under DC bias conditions.

3.6.2.1 Permeability

By far the most important single property of ferromagnetic is their high relative permeabilities. The permeability of a ferromagnetic is not constant as a function of magnetic field in the way that the permeability of a paramagnetic is. The magnetic permeability, μ, of a particular material is defined as the ratio of flux density, B to field strength, H, within it, as shown below:

$$\mu = B / H \quad (Hm^{-1}) \qquad \text{.............(1)}$$

Instead, in order to characterize the properties of a given ferromagnetic material it is necessary to measure the magnetic induction, B as a function of H over a continuous range of H to obtain a hysteresis or magnetization curve.

For ferromagnetic materials, the initial relative permeabilities usually lie in the range 10- 10^5. The highest value occurs for special alloys such as permalloy and supermalloy, which are nickel-iron alloy. The graph in **Figure 3.6** shows the values of permeability of iron.

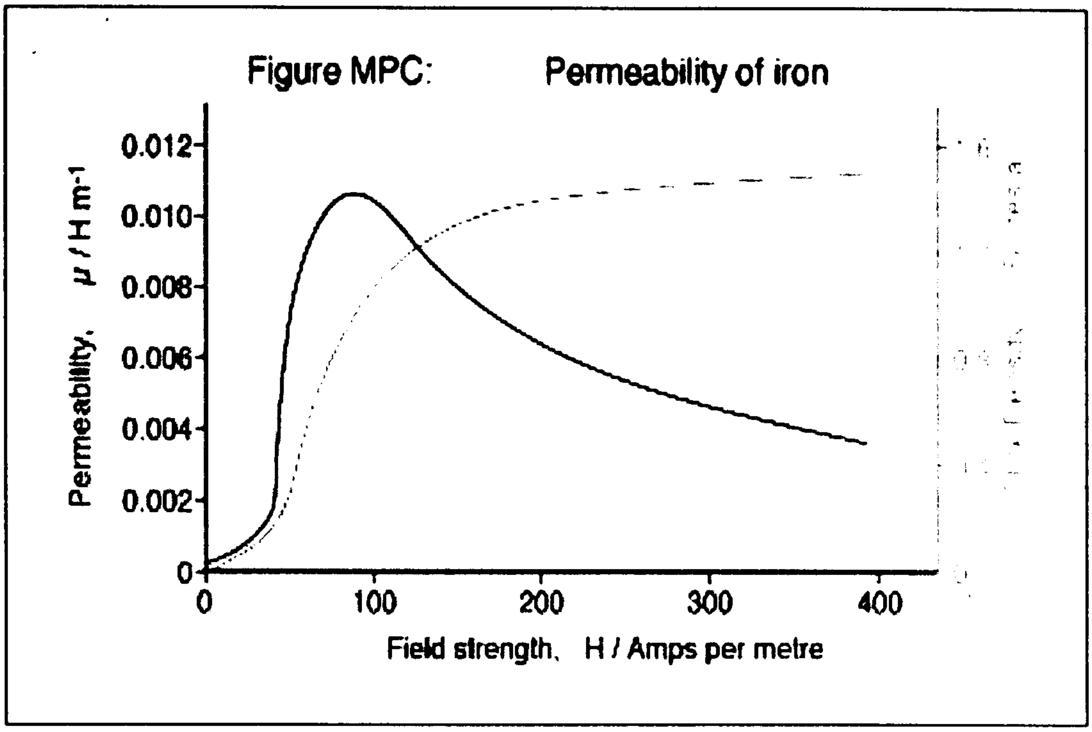


Figure 3.6: Permeability of Iron

3.6.2.2 Relative Permeability

Relative permeability is a very frequently used parameter. It is a variation upon 'straight' or absolute permeability, μ, but is more useful because it makes clearer how the presence of a particular material affects the relationship between flux density and field strength. The term 'relative' arises because this permeability is defined in relation to the permeability of a vacuum, μ_o, where

$$\mu_r = \mu / \mu_o \qquad ....(2)$$

Initial permeability, μ_i, describes the relative permeability of a material at low values of B (below 0.1T). The maximum value for μ in a material is frequently a factor 5 or more above its initial value. **Table 3.3** below shows the approximate maximum values of relative permeability of various types of ferromagnetic materials with their several applications.

Table 3.3: Approximate maximum permeabilities for ferromagnetic materials.

Material	μ/H m^{-1}	μ_r	Application
Ferrite U 60	1.00E-05	8	UHF chokes
Ferrite M33	9.42E-04	750	Resonant circuit RM cores
Nickel (99% pure)	7.54E-04	600	-
Ferrite N41	3.77E-03	3000	Power circuits
Iron (99.8% pure)	6.28E-03	5000	-
Ferrite T38	1.26E-02	10000	Broadband transformers
Silicon GO steel	5.03E-02	40000	Dynamos, mains transformers
supermalloy	1.26	1000000	Recording heads

3.6.2.3 Hysteresis

The most common way to represent the bulk magnetic properties of a ferromagnetic material is by a plot of magnetic induction B for various field strengths H. Alternatively plots of magnetization M against H are used, but these contain the same information since $B = \mu_o (H + M)$. The hysteresis was introduced by Ewing [2] who was the first to systematically investigate it. A typical hysteresis loop is shown in **Figure 3.7.**

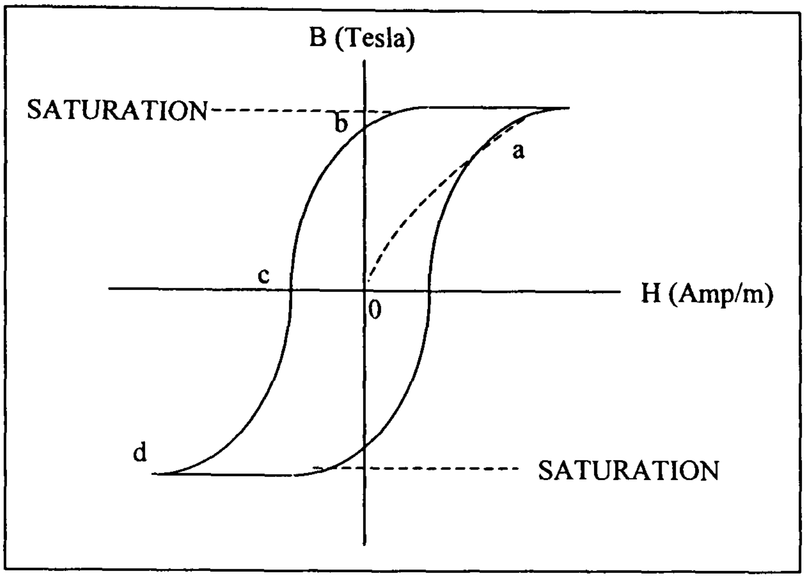


Figure 3.7: A typical hysteresis loop

The suitability of ferromagnetic materials for applications is determined principally from characteristics shown by their hysteresis loops. The origin of coordinates *0* represents the unmagnetized condition of ferromagnetic materials. When a magnetizing force is applied, the sample proceeds along the *0* to *a* line to point *a* as the magnetic polarization increases. This line is known as the *magnetization curve.*

When the magnetizing forces at point *a* reduced, the flux density does not reduce back along the magnetization curve, but displays higher values. When *H* has been reduced to zero, *B* still has a positive value indicated by point *b*, which is known as the ***remanence,*** a measure of its ***retentivity.*** This phenomenon is known as ***hysteresis.***

In order to bring *B* back to zero, the magnetizing force must be made negative, to a value indicated by point *c* where *H* has a value known as the *coercive force*, a measure of its ***coercivity.*** When *H* is varied periodically about the origin the closed contour is known as a *hysteresis loop.*

3.6.2.4 Saturation Magnetization

From the hysteresis plot it can be seen that the ferromagnetic in its initial state is not magnetized. For a certain value of H, when little increase in B; the material is approaching the saturation. Different materials saturate at different values of flux density. At the saturation point, the permeability is very small or zero.

3.6.2.5 Coercivity

The magnetic induction can be reduced to zero by applying a reverse magnetic field of strength H_c. This field strength is known as the *coercivity*. It is strongly dependent on the condition of the sample, being affected by such factors as heat treatment or deformation.

The intrinsic coercivity, denoted H_{ci}, is defined as the field strength at which the magnetization M is reduced to zero. In soft magnetic materials H_c and H_{ci} are so close in value that usually no distinction is made. However, in hard magnetic materials there is a clear difference between them, with H_{ci} always being larger than H_c.

3.6.2.6 Curie Temperature

All ferromagnetic when heated to sufficiently high temperatures becomes paramagnetic. The transition temperature from ferromagnetic to paramagnetic behavior is called the *Curie temperature.* At this temperature the permeability of the material drops suddenly and both coercivity and remanence become zero.

3.6.2.7 Remanence

When the field is reduced to zero, after magnetizing a magnetic material the remaining magnetic induction is called the *remanent induction* B_R and the remaining magnetization is called the remanent magnetization M_R.

$$B_R = \mu_o M_R \qquad \text{……..(3)}$$

The remanence is used to describe the value of either the remaining induction or magnetization when the field has been removed after the magnetic material has been magnetized to saturation. The remanent induction or magnetization is used to describe the remaining induction or magnetization when the field has been removed after magnetizing to an arbitrary level. The remanence therefore becomes the upper limit for all remanent inductions or magnetizations. **Table 3.4** below shows the magnetic properties of ferromagnetic materials.

Table 3.4: Magnetic Properties of Ferromagnetic Materials

Material	Treatment	Initial Relative Permeability	Maximum Relative Permeability	Coercive Force	Remanent Flux Density
Iron, 99.8% pure	Annealed	150	5000	1.0	13,000
Iron, 99.95% pure	Annealed in hydrogen	10,000	200,000	0.05	13,000
78 Permalloy	Annealed, quenched	8,000	100,000	.05	7,000
Superpermalloy	Annealed in hydrogen, controlled cooling	100,000	1,000,000	0.002	7,000
Cobalt, 99% pure	Annealed	70	250	10	5,000
Nickel, 99% pure	Annealed	110	600	0.7	4,000
Steel, 0.9% C	Quenched	50	100	70	10,300
Steel, 30% Co	Quenched	...	...	240	9,500
Alnico 5	Cooled in magnetic field	4	...	575	12,500
Silmanal	Baked	...	...	6,000	550
Iron, fine powder	Pressed	...	...	470	6,000

3.7 Historical Background of Fluxgate Magnetometer

The fluxgate magnetometers are the most widely used sensor for compass navigation system, was first developed about 1928 and later refined by the military for submarine detection. The devices have also been used for geophysical prospecting and airborne magnetic field mapping operations.

Fluxgate sensors combine good sensitivity with relative ease of construction. It measures the magnitude and direction of the DC or low frequency AC magnetic field in the range of approximately 10^{-10} to 10^{-4} T. They are reliable, rugged, very low energy consumption and can reach up to 10pT resolution and 1nT long-term stability [10].

Fluxgate has advantages over other types of field sensors in certain area of field intensities and frequency measurements. It is much cheaper than the more sensitive magnetic sensors SQUID and need no liquid helium for operation. Fluxgates are the best selection if resolution in the nanotesla range is required. They may have a noise level comparable to that of a high temperature SQUID, but a much larger dynamic range [1]. The main fields of application of fluxgate sensors are: geophysical measurements; space research; identification; location and compasses; measurements of electric current and non-destructive measurements [9].

The basic sensor principle is illustrated in **Figure 3.8**, consists of two coils, a primary (used as the excitation or drive coil) and a secondary (used as the output or sensing coil), wrapped around a common high-permeability ferromagnetic core. The core's magnetic induction changes in the presence of an external magnetic field.

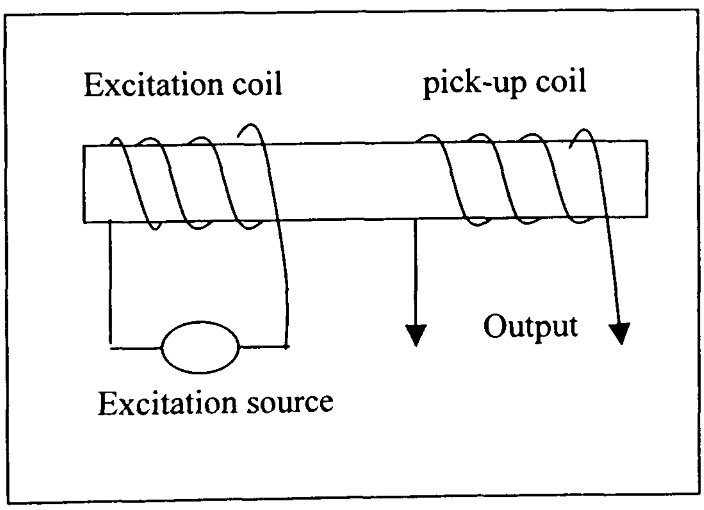


Figure 3.8: Basic form of fluxgate magnetometer

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